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MUZZLE EXIT (SET FORWARD) EFFECTS ON PROJECTILE DYNAMICS

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The resulting vibration after the removal of the load would be a free vibration if it were not for material damping, Coulomb damping (friction) at all of the interfaces and joints, aerodynamic drag, and any other damping caused by the cargo or warhead material (fig. 1). In figure 1, we see that during the set back event all of the material, and therefore the center of gravity (C.G.), moves rearward relative to the base when a force is applied to the base. Upon release of this load, the ends of the projectile oscillate about the C.G.

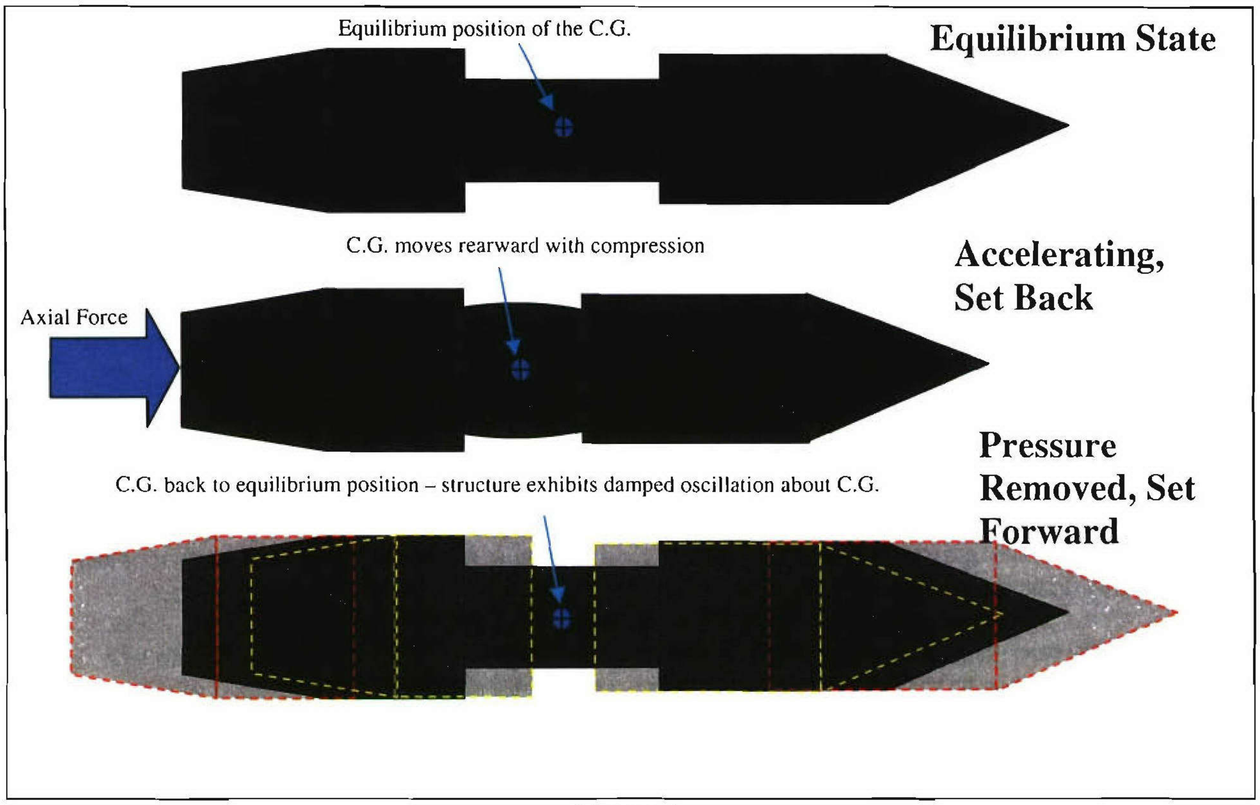

Figure 1
Illustration of a set forward event

EXAMPLES OF SET FORWARD FOR DIFFERENT MUNITIONS

Figures 2 and 3 show the acceleration time history of an 155-mm M898 Sense and Destroy Armor (SADARM) projectile in an XM297 (Crusader) and an M199 gun tube, respectively. The set forward acceleration is depicted as a magnified insert. The muzzle exit pressure was approximately the same for both configurations, however, the muzzle brake on the Crusader weapon was of a different geometry and allowed the pressure to decay slower than the M199 tube. For the Crusader gun tube, the magnitude of set forward acceleration is less and the response shows fewer vibrations than for the M199 gun tube.

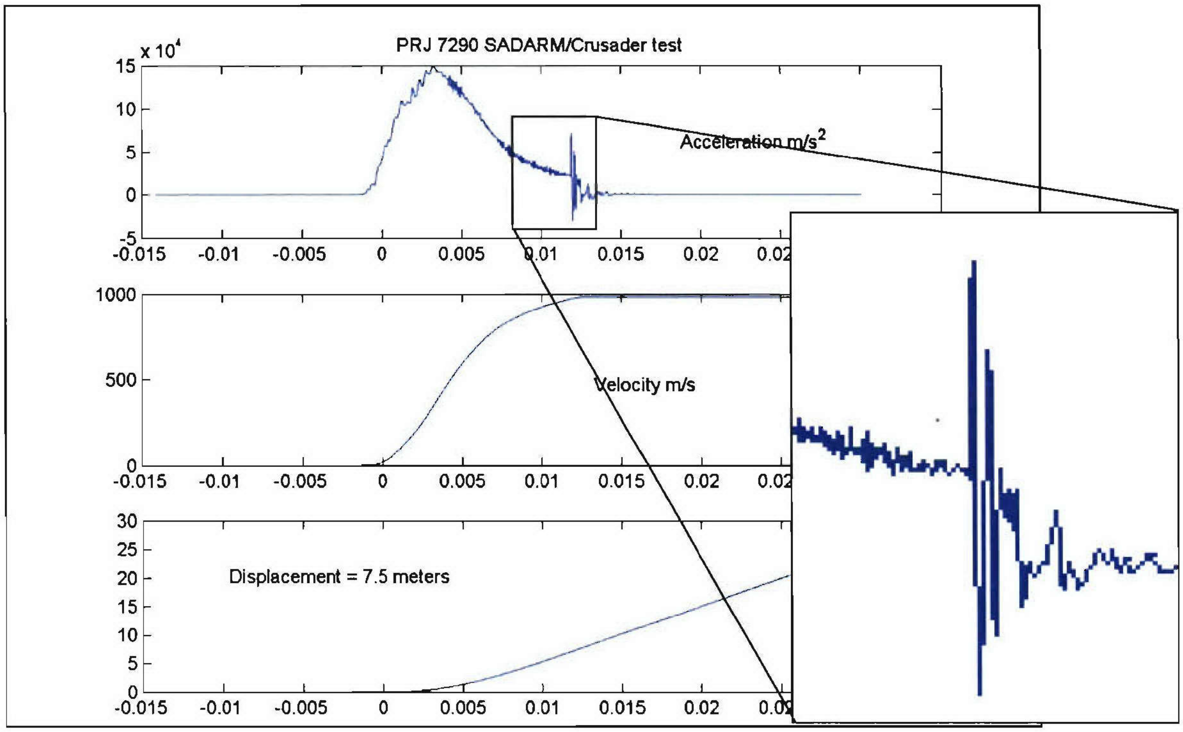

Figure 2
Set forward of a 155-mm M898 (SADARM) projectile in an XM297 gun tube

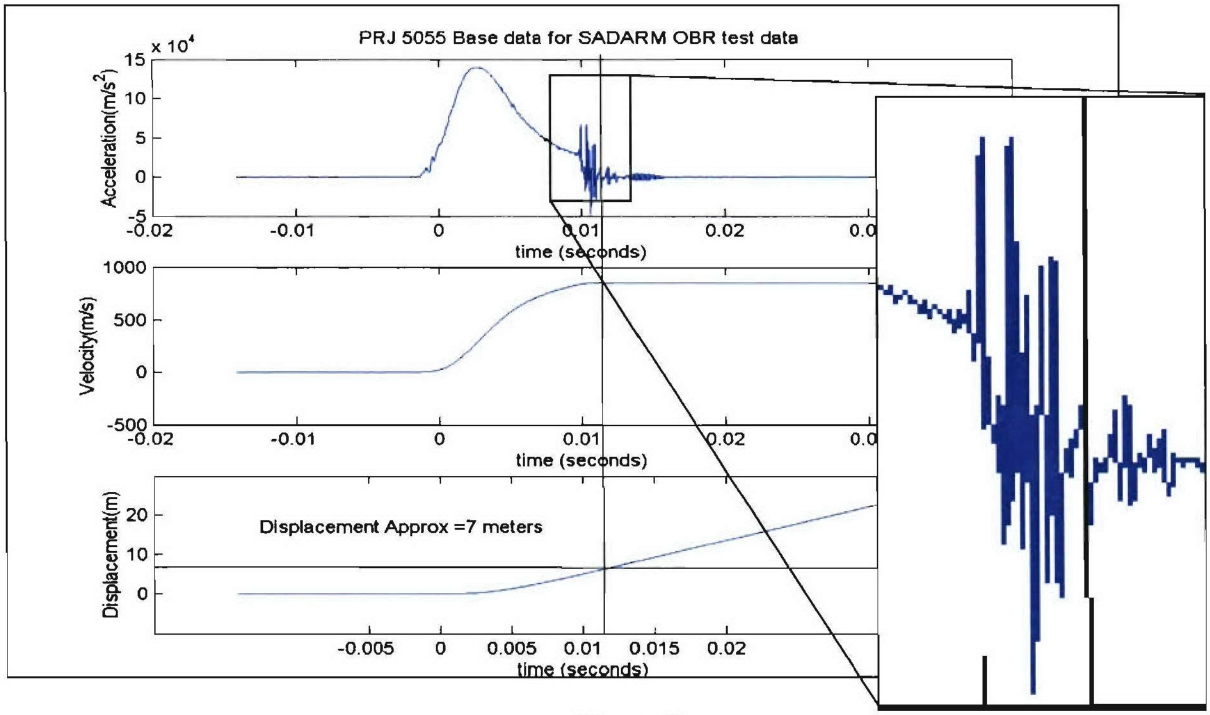

Figure 3
Set forward of a 155-mm M898 (SADARM) projectile in an M199 gun tube

Figure 4 shows the acceleration history in the axial and two orthogonal radial (balloting) directions in the ARDEC ballistic rail gun (BRG). This gun system is a test apparatus for the 155-mm projectile Excalibur. The projectile is fired from an M114A1 howitzer into a set of rails that gradually sink into a water trough. The ogive of the projectile is replaced by a scoop, which decelerates the projectile. This data curve is important because many gun launched electronic subsystems are tested in the device to avoid the cost of a standard projectile firing. The set forward levels experienced in this test are more severe than tactical firings.

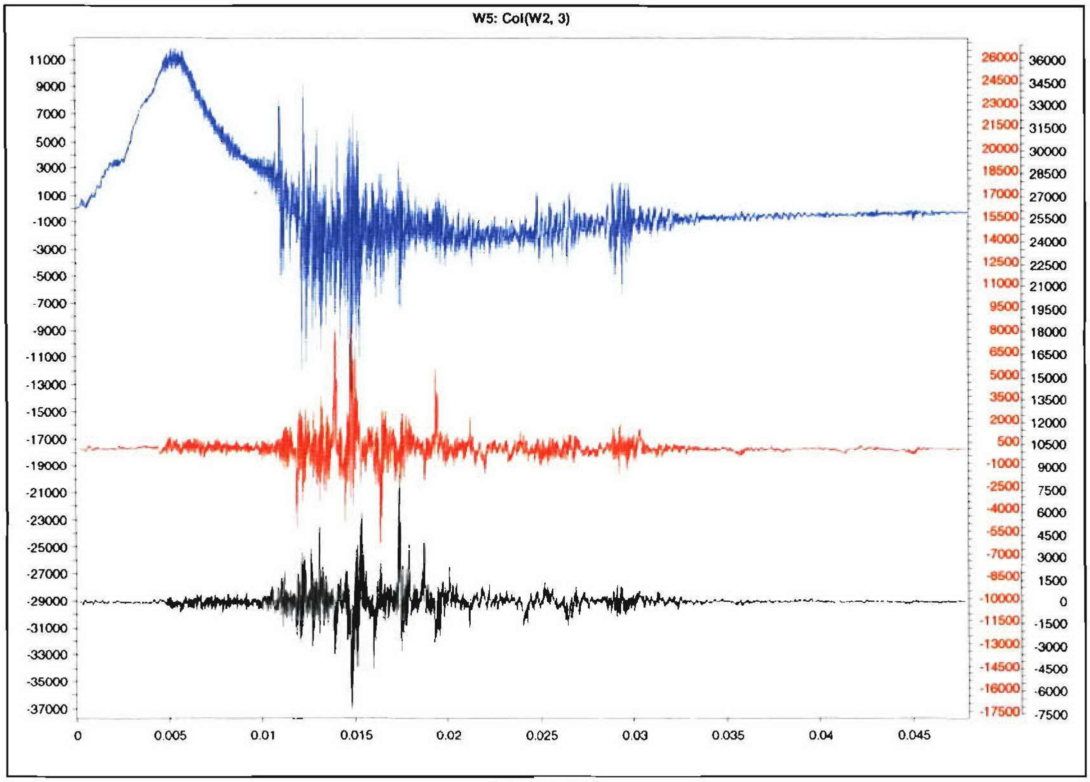

Figure 4
Acceleration time history of a typical projectile fired in the ARDEC BRG

Figure 5 shows a 120-mm practice projectile fired in a tank gun. Although the peak acceleration of this curve is 25% greater than that of the 155-mm howitzer firings, the levels of set forward are comparable. Again, this may be due to the gun or muzzle exit design or it may be due to the design of the propelling charge.

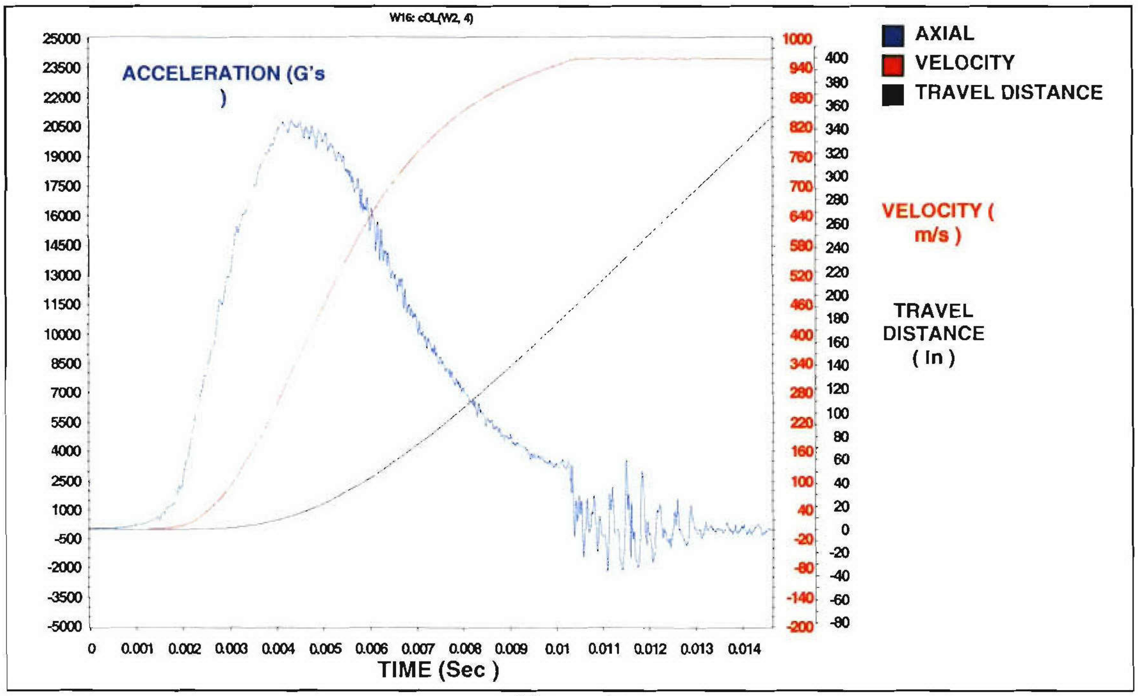

Figure 5
Acceleration time history of a typical projectile fired in a 120-mm tank cannon

Figure 6 shows a typical 120-mm mortar firing. Mortars appear to be unique in that there really is no discernable set forward oscillation. Although the data is scanty and more research is being performed in this area, this has been generally accepted as the case by ARDEC engineers.

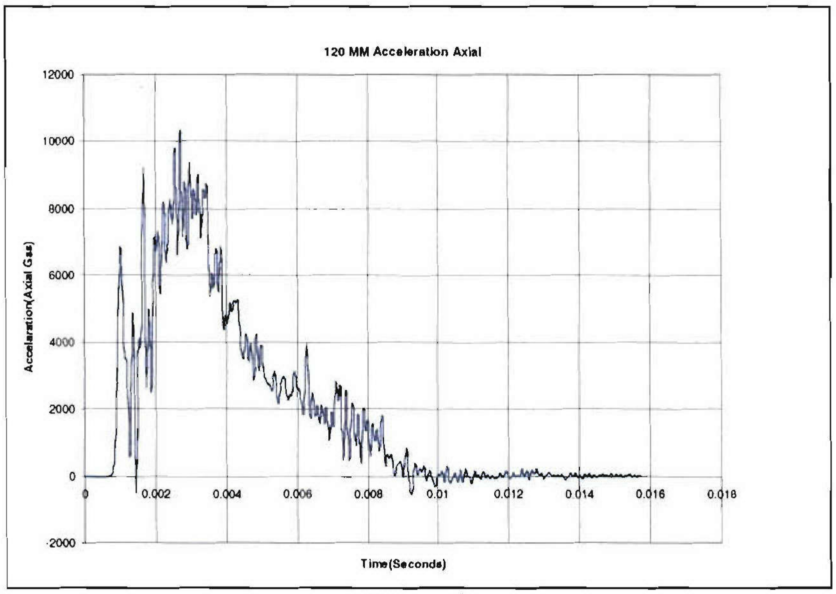

Figure 6
Acceleration time history of a typical projectile fired in a 120-mm mortar tube

PARAMETERS THAT MAY AFFECT SET FORWARD

Several years of data were examined to determine if the root cause of high set forward accelerations could be determined before munitions were designed and tested. The following factors were investigated:

- Muzzle exit pressure
- Set back pressure
- Length of the projectile

Muzzle Exit Pressure

One of the commonly held assumptions is that set forward is a function of the magnitude of the muzzle exit pressure. Test results from the Excalibur, a 155-mm projectile, program were reviewed. The pressure was measured at a pressure tap near the muzzle of the gun. The set forward acceleration was the minimum recorded axial acceleration on-board the projectile. Figure 7 shows a plot of the muzzle exit pressures and set forward for 27 live-fire shots. The figure shows a trend line. The correlation of $R^2 = 0.2$ is a weak correlation of the data to a straight line. The results include several types of gun tubes.

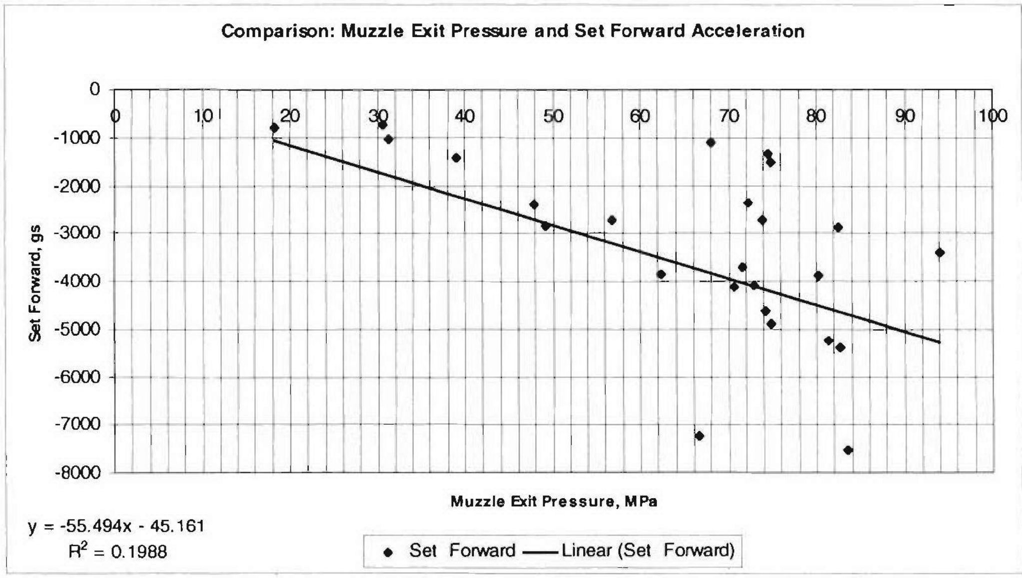

Figure 7
Set forward as a function of measured base pressure, Excalibur, 155-mm diameter

Correlation with Set Back Acceleration and Transverse Acceleration

Designers often assume that the set forward acceleration is 1/3 of the set back acceleration. Figure 8 shows a comparison from the same Excalibur data set as used for figure 7. The $R^2 = 0.12$ indicates a weak correlation between set forward and set back accelerations.

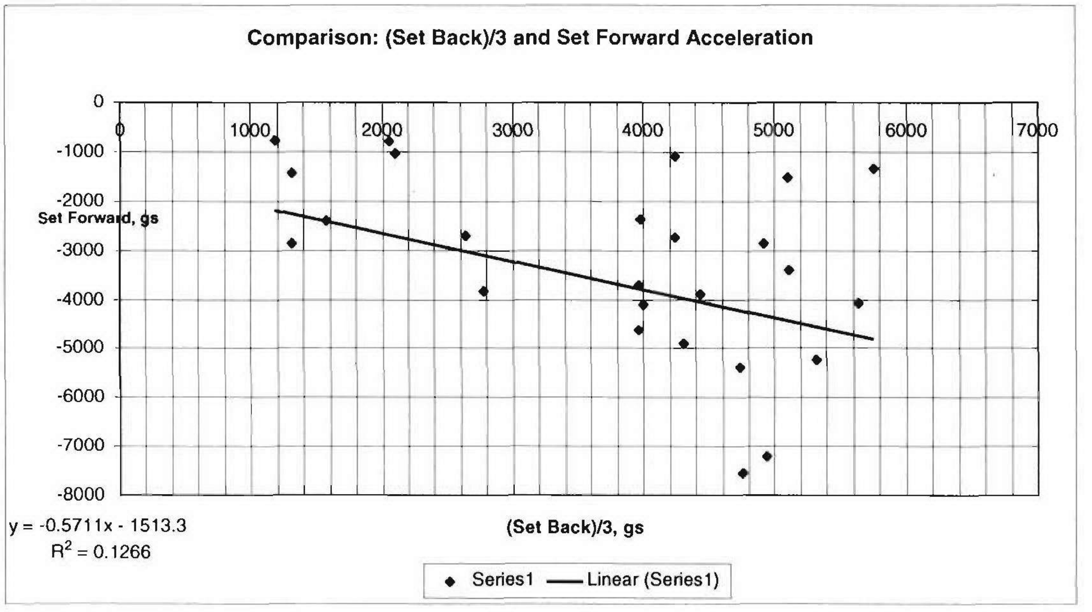

Figure 8
Set forward as a function of set back, Army's Excalibur projectile

The set forward acceleration and the maximum transverse acceleration both occur at muzzle exit. Figure 9 shows the correlation, again relatively weak, between set forward and transverse acceleration.

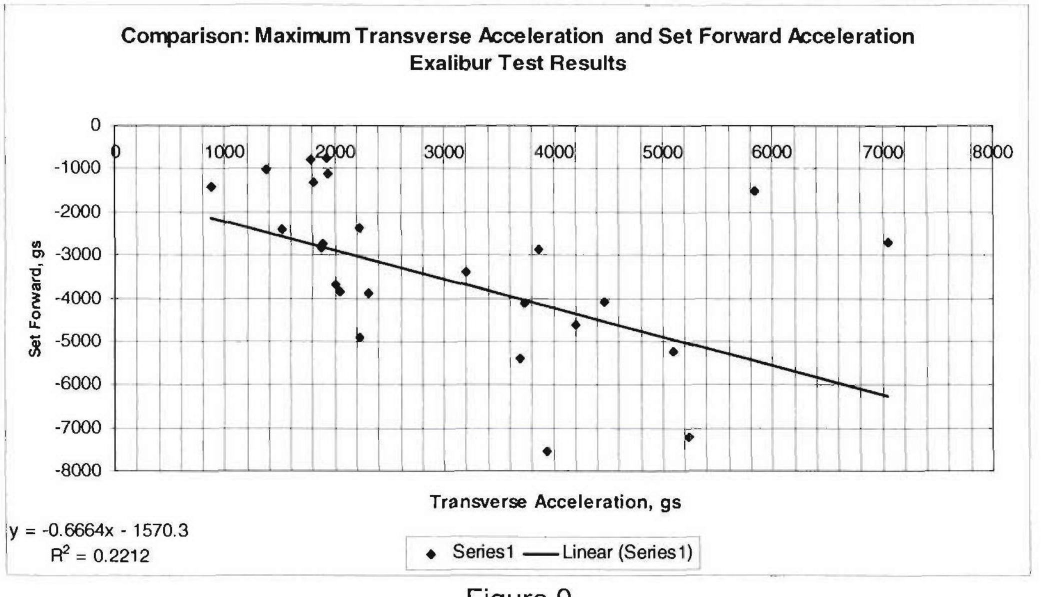

Figure 9
Set forward as a function of measured transverse acceleration at muzzle exit, Excalibur

Set Forward and Projectile Length

Method -- A numerical experiment was performed by Benet Weapons Laboratory to determine if longer projectiles are subject to larger set forward loads. The purpose of this analysis was to determine if projectile length and weight affect the set-forward accelerations of an artillery projectile.

The SIMBAD (ref. 5) code was modified to give the accelerations of the projectile nodes as an output file. The length of a generic projectile was varied for two different cases: first, with the weight varying with the length; and second, with the weight remaining constant. The axial accelerations of the projectile nodes were tabulated and plotted.

The projectile model was based on the 155-mm M795 geometry and weight, with the length being varied ±0.1 m. Two different weight assumptions were used. First, the weight varied by retaining the shell thickness, thus letting the length determine the weight. Second, the length varied, but the projectile weight remained constant. The projectile properties used to analyze the first case are provided in table 1.

Table 1
Projectile properties used in SIMBAD runs where projectile weight varied with length

Designation	Length (m)	Mass (kg)	C.G. location (m)	SIMBAD .sho file
A	0.7032	30.012	0.2928	Flex155_A
B	0.7282	39.382	0.3034	Flex155_B
C	0.7532	40.787	0.3140	Flex155_C
D	0.7782	42.098	0.3244	Flex155_D
baseline	0.8032	43.359	0.3356	Flex155_nodes
E	0.8282	44.618	0.3452	Flex155_E
F	0.8532	45.984	0.3557	Flex155_F
G	0.8782	47.375	0.3663	Flex155_G
H	0.9032	48.793	0.3769	Flex155_H

The initial SIMBAD runs were made using the NLOS-C BTA tube and M182 gun mount. Two different projectiles were used. The pressure and acceleration data for the M795 projectile was used initially, and then runs were made with the data from the M549A1 projectile. The M795 ballistic data resulted in a muzzle velocity of 700 m/s for the baseline projectile and the M549A1 data gave a corresponding muzzle velocity of 754 m/s. The data was tabulated out to 0.021 sec, with shot exit being at 0.0131 to 0.125 sec for the two sets of data.

Results, Effect of Projectile Length

The SIMBAD code printed the projectile node accelerations at each integration step, every 0.0000005 sec. The data shows that the nodes oscillate forward and back, with the smallest values and ranges being at the nodes closest to the C. G. The end nodes show larger accelerations than the center nodes, with the forward end showing the largest values.

Tables 2 and 3 show results for the M795 and M549A1 projectiles, respectively. The maximum and minimum accelerations for each projectile model are given for nodes 1 (base), 5 (closest to C.G.), and 11 (tip). The accelerations are given in g's. Figures 10 and 11 show correlations where the projectile mass varies with length. For the M795 projectile, the correlation of set forward acceleration is about 0.5 at the base and lower at the center of mass and forward section. For the M549A1 projectile, the correlation is strongest at the center of mass and weakest at the forward section. The set forward acceleration is also a function of the distance from the center of mass of the projectile. The base is closer to the center of mass and has a lower set forward acceleration for both projectiles.

Table 2
Results: SIMBAD runs using an M795 projectile geometry

Mass Varies		Node	M795 Pres, Acc (700 m/s) Max	Min	M795 Pres, Acc (700 m/s) Max	Min	Constant Mass	
Projectile:	A	1	5914.4	-4782.5	3436.4	-4058.5	Projectile:	A2
Length:	0.7032	5	2059.8	-1764.1	1927.3	-1682.5	Length:	0.7032
Mass	38.012	11	7607.1	-8331.1	8647.2	-6923.9	Mass	43.365
Projectile:	B	1	4751.9	-2386.1	3018.4	-4007.5	Projectile:	B2
Length:	0.7282	5	2294.4	-1947.7	1580.6	-2019.0	Length:	0.7282
Mass	39.382	11	4568.3	-7953.8	7291.0	-5282.1	Mass	43.361
Projectile:	C	1	4466.4	-4925.2	4282.8	-4456.2	Projectile:	C2
Length:	0.7532	5	2386.1	-2059.8	2355.5	-1764.1	Length:	0.7532
Mass	40.787	11	8800.2	-8218.9	5435.1	-8382.1	Mass	43.352
Projectile:	D	1	4486.8	-4395.0	5027.2	-4762.1	Projectile:	D2
Length:	0.7782	5	2100.6	-2151.6	2365.7	-1764.1	Length:	0.7782
Mass	42.098	11	8596.2	-9952.4	8504.4	-10299.1	Mass	43.362
Projectile:	Baseline	1	3844.3	-3630.2	3844.3	-3630.2	Projectile:	Baseline
Length:	0.8032	5	2192.4	-1998.6	2192.4	-1998.6	Length:	0.8032
Mass	43.359	11	8280.1	-9830.1	8280.1	-9830.1	Mass	43.359
Projectile:	E	1	4700.9	-6271.3	5904.2	-6291.6	Projectile:	E2
Length:	0.8282	5	2906.2	-2926.6	2651.3	-2967.4	Length:	0.8282
Mass	44.618	11	8218.9	-9789.3	8249.5	-9605.7	Mass	43.367
Projectile:	F	1	5792.0	-5190.4	5353.5	-4293.0	Projectile:	F2
Length:	0.8532	5	2192.4	-2375.9	1876.3	-2182.2	Length:	0.8532
Mass	45.984	11	8993.9	-9717.9	7943.6	-10696.8	Mass	43.361
Projectile:	G	1	5445.3	-6475.2	4792.7	-5679.8	Projectile:	G2
Length:	0.8782	5	3324.3	-1886.5	3375.3	-1631.5	Length:	0.8782
Mass	47.375	11	9830.1	-8545.2	10411.3	-7545.9	Mass	43.365
Projectile:	H	1	4884.4	-6383.4	5322.9	-9830.1	Projectile:	H2
Length:	0.9032	5	2630.9	-2824.6	3273.3	2987.8	Length:	0.9032
Mass	48.793	11	9289.6	-9106.1	7851.8	-8739.0	Mass	43.358

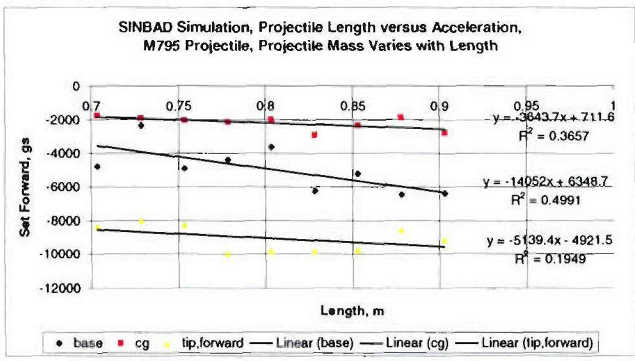

Figure 10
Results: SIMBAD analysis of the M795 projectile

Table 3
Results: SIMBAD runs using an M549A1 projectile geometry

		Node	M549A1 Pres, Acc (754 ms) Max	M549A1 Pres, Acc (754 ms) Min	M549A1 Pres, Acc (754 ms) Max	M549A1 Pres, Acc (754 ms) Min		
Projectile:	A	1	1488.8	-1254.3	1580.6	-1448.0	Projectile:	A2
Length:	0.7032	5	489.5	-418.1	540.4	-805.6	Length:	0.7032
Mass	38.012	11	2110.8	-2569.7	2100.6	-2814.4	Mass	43.365
Projectile:	B	1	1437.8	-652.6	1325.6	-1764.1	Projectile:	B2
Length:	0.7282	5	499.7	-530.3	346.7	-479.3	Length:	0.7282
Mass	39.382	11	1162.5	-1957.9	3130.5	-1968.1	Mass	43.361
Projectile:	C	1	1988.4	-1774.3	1101.3	-1662.1	Projectile:	C2
Length:	0.7532	5	866.8	-673.0	540.4	-489.5	Length:	0.7532
Mass	40.787	11	2314.8	-3762.8	3008.2	-1376.6	Mass	43.352
Projectile:	D	1	989.1	-683.2	897.4	-1142.1	Projectile:	D2
Length:	0.7782	5	499.7	-469.1	367.1	-377.3	Length:	0.7782
Mass	42.098	11	1539.8	-1162.5	1855.9	-1978.2	Mass	43.362
Projectile:	Baseline	1	1529.6	-1906.9	1529.6	-1906.9	Projectile:	Baseline
Length:	0.8032	5	917.7	-550.6	917.7	-550.6	Length:	0.8032
Mass	43.359	11	3813.7	-3844.3	3813.7	-3844.3	Mass	43.359
Projectile:	E	1	2008.8	-1672.3	1611.2	-815.8	Projectile:	E2
Length:	0.8282	5	846.4	-479.3	713.8	-377.3	Length:	0.8282
Mass	44.618	11	2477.9	-2294.4	2722.6	-2172.0	Mass	43.367
Projectile:	F	1	1070.7	-1182.9	509.9	-805.6	Projectile:	F2
Length:	0.8532	5	744.4	-927.9	897.4	-846.4	Length:	0.8532
Mass	45.984	11	2885.8	-1142.1	1539.8	-1254.3	Mass	43.361
Projectile:	G	1	1733.5	-1682.5	2039.4	-2223.0	Projectile:	G2
Length:	0.8782	5	1193.1	-764.8	1468.4	-744.4	Length:	0.8782
Mass	47.375	11	4853.8	-3324.3	3375.3	-3813.7	Mass	43.365
Projectile:	H	1	1274.6	-1957.9	2304.6	-1335.8	Projectile:	H2
Length:	0.9032	5	1458.2	-1366.4	734.2	-1295.0	Length:	0.9032
Mass	48.793	11	3171.3	-3436.4	2661.5	-3518.0	Mass	43.358

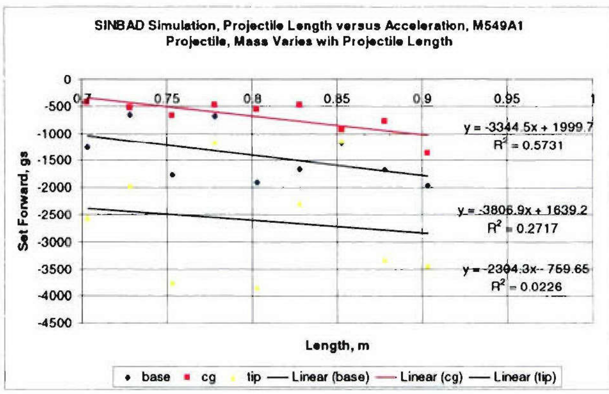

Figure 11
Results of SIMBAD analysis using an M549A1 projectile geometry

DISCUSSION: SYSTEM IMPLICATIONS OF SET FORWARD - ANALYSIS

From experience, if not correlations, some general design guidelines are suggested until the first projectiles components need to be designed for the relatively large set back acceleration. For projectile wall and base components, a simple quasi-static analysis can be performed and will result in an acceptable design. The load to use in this analysis is the 3 sigma upper limit of the gun system acceleration or the permissible maximum pressure (PMP) of the weapon (refs. 1 and 6).

Although the root cause of the sometimes high set forward accelerations is not known, a number of failures in the Army's SADARM and Excalibur projectiles can be traced to the muzzle exit event. For Excalibur, numerous capacitor failures occurred on the rearward side of circuit boards. Finite element analysis of the circuit board assemblies indicated that failure occurred during muzzle exit. The resulting recommendation is that all electronics components need to be designed for the muzzle exit accelerations: set forward with the maximum transverse accelerations. For the electronics, especially devices that are sensitive to frequency content, a full dynamic analysis is required. Several load curves should be used for the analysis to determine the response to different load frequencies. The direction of the transverse loads should also be varied as that changes circuit board curvature.

When joints are placed in the projectile load path it is important that they survive both set back and set forward. This usually presents a problem for the designers of cargo projectiles because threaded joints on a cargo projectile are designed to shear at as small a load as possible. Care must be taken in the design of these joints because the joint must be strong enough to survive muzzle exit, but weak enough for a gentle expulsion. A method developed by Pangburn (ref. 7) was proven successful in the design of threaded joints.

Another issue with threaded joints surviving muzzle exit is inspecting the joint to assure that the treads meet specification. It has been shown on the M898 SADARM program as well as on the M31 mortar fin assembly that inspecting threads using only "go" and "no-go" gages results in parts that have failed in testing and can cause hazards by having malformed threads. These threads were manufactured by double cutting, which is typically not observed when using go and no-go gages.

The Analysis and Evaluation Technology Division of ARDEC is performing research to determine if simple quasi-static compression of the projectile structure to muzzle exit acceleration loadings and instantaneous release will suffice for set forward design. The results to date are not conclusive. Experimental verification with a statistically significant number of samples of the correct projectile structure is usually necessary. To obtain the data, these projectiles must contain some sort of on-board instrumentation.

CONCLUSIONS

Set forward is a highly dynamic condition that occurs when a projectile exits the muzzle of a weapon. The levels of this acceleration, as well as the frequency, are dependent upon the projectile structural characteristics, length, and muzzle exit pressure. The set forward event can not, in general, be modeled using quasi static techniques. A dynamic analysis must be performed, especially for sensitive electronic components. Proper inspection of critical joints in the load path must be done with methods other than just using "go" and "no-go" thread gages.

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